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B. Lites, M. Cheung, T. Magara, J. Mariska, and K. Reeves

Internetwork Horizontal Magnetic Fields in the Quiet Sun Chromosphere: Results from a Joint *Hinode*/VTT Study

Andreas Lagg,[1,2] Ryohko Ishikawa,[1] Laura Merenda,[2]
Thomas Wiegelmann,[2] Saku Tsuneta,[1] and Sami K. Solanki[2]

Abstract. We present results from a joint *Hinode*/VTT campaign (May 2008). Spectropolarimetric data of a quiet Sun super-granular network cell at a heliocentric angle of 28° in the He I 10830 Å line were analyzed using an inversion code incorporating Hanle and Zeeman effects (HeLIx$^+$) to retrieve magnetic field strength and direction in the upper chromosphere. Simultaneously recorded *Hinode* SOT/SP data reveal the photospheric magnetic field morphology, clearly showing magnetic flux concentrations in the internetwork. The photospheric magnetic field maps are used to feed potential field extrapolations similar to the work by Schrijver and Title (2003). The extrapolated magnetic field structure is compared with the magnetic field configuration resulting from the He 10830 inversions. These inversions also reveal horizontal magnetic structures extending over a length of up to 20 Mm above the internetwork, indicative of the presence of a magnetic canopy. The photospheric magnetic flux concentrations in the internetwork are obviously not sufficiently strong to prevent the formation of a canopy at chromospheric heights.

1. Introduction

Obtaining the chromospheric magnetic field vector over quiet Sun areas from observations is a difficult task. The formation process of the He I 10830 Å line, involving coronal illumination to populate the ground state of the transition (Avrett et al. 1994; Centeno et al. 2008) and therefore lacking any photospheric contribution, provides us with a unique tool to address this difficulty.

Major improvements in the physical understanding and modeling of the polarization signals of the He I 10830 Å triplet (Trujillo Bueno et al. 2002; Socas-Navarro et al. 2004; Trujillo Bueno et al. 2005; Merenda et al. 2006; Trujillo Bueno and Asensio Ramos 2007) resulted in the development of HAZEL (from HAnle and ZEeman Light), a user-friendly and reliable inversion code to retrieve the chromospheric magnetic field morphology taking into account the joint action of atomic level polarization and the Hanle and Zeeman effects (see Asensio Ramos, Trujillo Bueno, and Landi Degl'Innocenti 2008). Given that in our previous investigations we have been applying the inversion code HeLIx (**He**lium **L**ine **I**nformation E**x**tractor, Lagg et al. 2004), which did not take into account the impact of atomic level polarization, we have found it convenient to perform the application shown here using an improved version we have called

[1]National Astronomical Observatory of Japan, Tokyo

[2]Max-Planck-Institut für Sonnensystemforschung, Katlenburg-Lindau, Germany

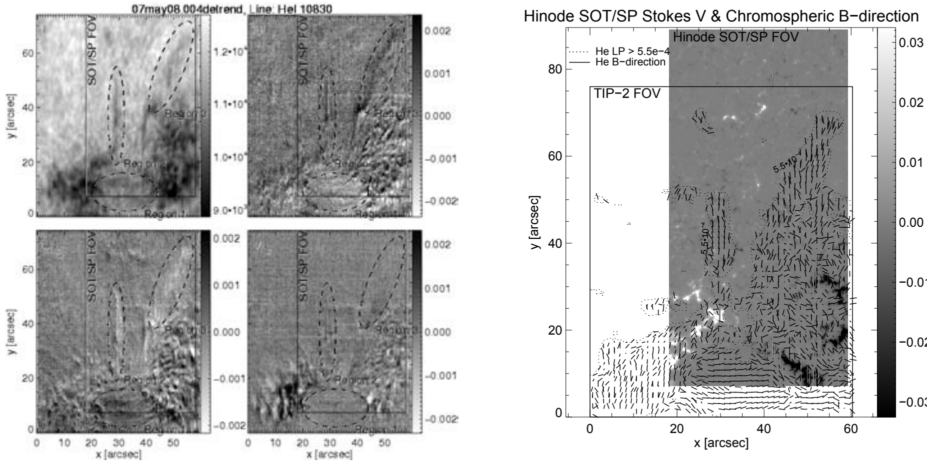

Figure 1. *Left:* Chromospheric Stokes I, Q, U and V map of the observed region. Dashed ellipses mark regions 1, 2 and 3 (see text), the boxes show the alignment with the SOT/SP data. *Right:* Photospheric *Hinode* SOT/SP Stokes V map in the red wing of the Fe I 6301.5 Å line. Contour lines enclose regions where a reliable determination of the magnetic field direction is possible (linear polarization signal in He I $\geq$ $5.5 \cdot 10^{-4}$. Black lines show the azimuthal direction of the chromospheric magnetic field as retrieved by HeLIx$^+$ inversions of the He I data. The rectangular box shows the TIP-II field-of-view.

HeLIx$^+$ (see also Lagg et al. 2009), which is based on the forward modeling calculation module of HAZEL. For a detailed presentation of the quantum theory of the Hanle and Zeeman effects we refer the reader to the monograph by Landi Degl'Innocenti and Landolfi (2004).

The aim of this study is to investigate further the possible presence of a magnetic canopy above internetwork cells (see also Lagg (2007), and sections 3.3 and 5.4 in Asensio Ramos et al. 2008). According to potential field extrapolations performed by Schrijver and Title (2003), relatively strong internetwork magnetic flux concentrations inhibit the formation of a canopy over the internetwork. These flux concentrations were recently measured by the *Hinode* spacecraft (Lites et al. 2008; Ishikawa et al. 2008). The study presented here uses data from the spectropolarimeter of the *Hinode* Solar Optical Telescope (SOT/SP, Tsuneta et al. 2008) to provide the photospheric background for the chromospheric measurements in the He I 10830 Å line.

2. Observations

We analyze data from a joint *Hinode*/VTT campaign (*Hinode* Operation Plan HOP 71) of the decaying active region 10993, observed on May 7, 2008 at a heliocentric angle of 28° ($\mu = 0.90$, solar position $x = 50''$, $y = 400''$) with the *Hinode* SOT/SP (*normal mode*, 4.8 s exposure time per slit position, 0. ″16 step size) and the Tenerife Infrared Polarimeter II (TIP-II, Collados et al. 2007) mounted behind the German Vacuum Tower Telescope (VTT) on Tenerife, Spain. Co-alignment and field-of-view are displayed in Fig. 1 showing on the left the Stokes parameter maps of the He I line, integrated over the line core of the red lines of the He I 10830 Å triplet (transitions 2 and 3, see Lagg et al. 2007), and on the right a Stokes V map of the SOT/SP observations. The region consisted of a weak network region (lower third of the map) and a relatively quiet region (top left part). The exposure time of 16 s per slit position and a spatial binning before applying the HeLIx$^+$ inversions to a pixel size of 0.″96 resulted in a signal-to-noise ratio of 4000 to 7000 for the TIP-II observations.

The maps shown in Fig. 1 (*left*) indicate the presence of chromospheric magnetic fields outside the photospheric network concentrations, seen in the He I Stokes Q, U and V maps. Faint chromospheric structures, best seen in the Stokes U map, connect the opposite photospheric polarities (region 1; marked in Fig. 1 The Stokes I, Q and U maps also show the presence of two elongated structures extending over the quiet Sun area (region 2: $x \approx 30''$, $y \approx$ 25-50″, and region 3: $x \approx$ 45-55″, $y \approx$ 45-65″).

3. Analysis Method

Using the HeLIx$^+$ code, we inverted the He I Stokes parameters using the Hanle slab model, as described in Trujillo Bueno and Asensio Ramos (2007). We used a one-component atmosphere including atomic polarization, Paschen-Back and Hanle effects. Magneto-optical effects were neglected. The free parameters for the model atmosphere are the magnetic field strength, inclination and azimuth, B, γ and φ (solar reference frame, only computed when the strength of the linear polarization exceeds $5.5 \cdot 10^{-4}$), the line of sight velocity, v_{LOS}, the damping constant a, the thermal broadening of the line, v_{Dopp}, the optical thickness of the slab, τ_{Slab}, and the height of the slab above the solar surface, h_{Slab}. A magnetic filling factor (FF) of unity was assumed. The Pikaia genetic algorithm was used for minimization (Charbonneau 1995). The nearby Si I 10827 Å was characterized by a Voigt function in order to compensate the reduction of the continuum level extending to the He I 10830 wavelength region.

The Fe I data from the *Hinode* SOT/SP instrument were inverted using the HeLIx$^+$ code in a Milne-Eddington type atmosphere with a stray-light component (10 free parameters, see Orozco Suárez et al. 2007) to obtain photospheric magnetic flux maps (not shown, see poster P5-4). The average horizontal and vertical flux maps were computed by applying a 4″ boxcar smoothing to the high resolution SOT/SP flux maps.

4. Results and Conclusions

The three regions indicated in Fig. 1 are dominated by unidirectional, horizontal chromospheric magnetic fields on scales of ≈20″.

Region 1: The inversion confirms that the magnetic field follows the filamentary structure seen in the chromospheric Stokes U maps of Fig. 1 Field strengths in this region are between 50 and 200 G. The structure is consistent with loop-like structures connecting the opposite polarity fields over the quiet, underlying photosphere.

Region 2: An approximately 5″ narrow spine with a horizontal magnetic field of ≈100 G extends 20″ over the an internetwork region with vertical magnetic flux densities between 10 and 15 $\mathrm{Mx\,cm^{-2}}$. The magnetic field azimuth follows the orientation of the spine.

Region 3: The underlying horizontal and longitudinal photospheric magnetic flux is extremely low. The chromospheric field morphology shows again nearly horizontal fields, tilted ≈20° with respect to the axis of the structure visible in the I, Q and V map. Field strengths range from 20 to 50 G. The field strengths lie in the Hanle saturation regime, where a reliable determination of the strength is impossible.

We compared the chromospheric magnetic field structure with potential field extrapolations (see Wiegelmann and Solanki 2004, not shown). Only in region 1 we could achieve a qualitative agreement of the extrapolated magnetic field morphology with the measured, regions 2 and 3 disagree in direction and strength of the field. The extrapolated magnetic field strength is on average a factor of 4 lower than the measured value.

The presented analysis shows that continuous, horizontal magnetic field structures at the height of the He I line formation, acting as a geometric separator between the network field opening into the solar atmosphere and the weak internetwork field, can exist above some parts of the quiet Sun photosphere (regions 2 and 3).

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